REFLOW OF NON-CIRCULAR NANO-PILLARS TO FABRICATE NANO-SCALE SOLID IMMERSION LENSES

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ABSTRACT

We investigate the reflow of non-circular, *i.e.*, triangular and square, shaped pillars to fabricate nano-scale solid immersion lenses (SILs). Electron beam lithography (EBL) and thermal reflow are the core of the fabrication process. For the optical characterization at λ = 642 nm, nano-SILs are replicated on a transparent substrate by soft lithography. The focal spots produced by the nano-SILs show both spot-size reduction and peak-intensity enhancement, which are consistent with the immersion effect.

INTRODUCTION

In 1990, Mansfield *et al.* proposed a new immersion technique for microscopy, called a solid immersion lens [1]. The SIL increases the numerical aperture [NA = $n\cdot\sin\theta$] by a factor of n (the refractive index of the SIL), as in liquid immersion. For a long time the fabrication of SILs was limited to macro-size, *i.e.* millimeter range dimensions, due to the lack of advanced fabrication technologies. The advance of micro- and nano-technology boosts the development of different types of SILs, for instance, diffractive SILs [2] and micro-scale SILs [3-5]. In our previous work, we demonstrated for the first time the fabrication and optical characterization of nano-scale SILs down to subwavelength size [6].

In this work, we diversify the fabrication of nano-SILs by employing non-circular shaped pillars, such as 400-nm square and 600-nm triangular patterns. Standard circular patterns are considered as well. Furthermore, the optimal designs and process conditions are investigated in order to achieve the ideal hemispherical structure. The performance of the fabricated nano-SILs is verified by measuring the intensity distributions of the immersed focal spots, which are compared to a reference non-immersion spot to reveal the diminution of the spot size and the enhancement of the peak intensity.

FABRICATION

Nano-scale pillars having several shapes are patterned by electron-beam lithography: 450 nm cylinders, 400 nm square pillars and 600 nm triangular pillars, which are shown in the scanning electron microscope (SEM) images of Fig. 1. We investigate two subjects. One is the reflow and the shape transformation of the non-circular pillars. The second is the optimal process conditions needed to produce the desired hemispherical structures after reflow. To do so, we vary the height [200 nm, 250 nm, 300 nm] and the diameter [420 nm or 480 nm] of the cylindrical patterns. Variation of the reflow temperature is also considered.

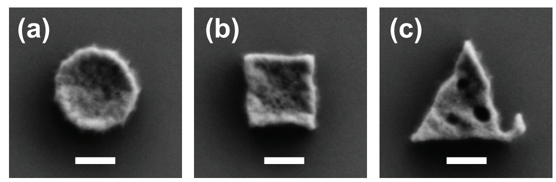

Fig. 1. SEM images of nano-pillars: (a) 450-nm circle, (b) 400-nm square and (c) 600-nm triangle. The scale bars indicate 200 nm.

To pattern a nano-pillar using EBL, an area of approximately 4 µm square with a void in the shape of the desired pillar at its center is exposed. Since polymethyl methacrylate (PMMA) is a positive resist, during the development process this area is removed, leaving a free-standing pillar of PMMA. As PMMA is also a thermoplastic, thermal reflow is applied to transform the flat-top pillar into a spherical structure. The glass transition temperature (T_g) of PMMA is approximately 110 ~ 120 °C, which mainly depends on the electron beam dose [7]. We heat samples above T_g by using a hot plate. At 120 °C, shape transformation is not observed except for surface smoothing and rounding of edges. When the reflow temperature is higher than 140 °C, the over-reflow causes widening of the lateral size and a reduction in the height of the SIL. Thus, the optimal reflow temperature is found to be 130 °C, where reflow speed is slow enough for better control compared to higher temperatures. Reflow at 130 °C for 50 min. leads to the full reflow of the pillars without the symptoms of over flow. Interestingly, both the square and triangular pillars are transformed into a circular shape after reflow. Since the volume of the pillar is very small, the heating to reflow temperature can lead to melting of the outer boundary, and wetting produces the spherical shape. In nano-scale fabrication, it is a challenging task to realize structures without errors (Fig. 1 demonstrates such issues). For example, the circle is slightly elliptic, and the square and the triangle are deformed as well. The reflow and wetting are a good solution to overcome this problem for the fabrication of nano-SILs, which essentially require spherical structures. The pillars are fabricated on silicon substrates to achieve the best resolution in EBL. For optical characterization with visible light (at λ = 642 nm), the reflowed spherical structures, *i.e.* the SILs, must be replicated on a transparent substrate. Soft lithography using a UV curable polymer (Norland, NOA 61, n = 1.56) enables replication of the SILs on borosilicate glass cover slips (thickness = 150 µm, n = 1.52). Figure 2 shows SEM images of the replicated nano-SILs on glass substrates.

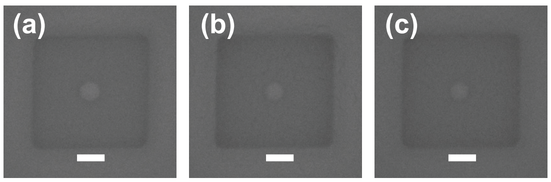

Fig. 2. SEM images of the replicated nano-SILs reflowed from the pillars shown in Fig. 1: (a) 450-nm cylindrical, (b) 400-nm square and (c) 600-nm triangular pillars, respectively. The scale bars indicate 1 µm. After reflow, all nano-SILs exhibit a spherical shape.

Figure 2 shows the 250-nm-height pillars after reflow. The cylinder is transformed into a SIL with diameter 630 nm, the square pillar to a 540-nm SIL, and the triangular pillar to a 630-nm SIL. More detailed quantitative analysis and dimensional characterization is ongoing, and will lead us to the optimal parameters for the hemi-spherical SIL.

OPTICAL CHARACTERIZATION

In this section, we verify the optical response of the fabricated SILs, which are shown in Fig. 2. The details of the optical characterization are reported elsewhere [6]. We measure the intensity distribution of the focal spot at the bottom of the SIL. For reference, we focus light at the interface between the air and the glass substrate [non-immersion spot] and compare this with the focal spot on the SIL [immersion spot]. Figure 3 shows the charge-coupled device (CCD) camera images and the intensity distributions of the reference spot and immersion spots through the nano-SILs of Fig. 2. In Fig. 3a, the dark spot in the center indicates the SIL, and the surrounding square is the region where the PMMA has been removed.

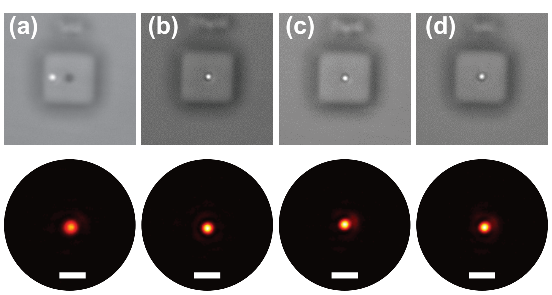

Fig. 3. CCD images and intensity distributions of the focal spots on the bottom plane of the SIL: (a) the reference spot, (b) - (d) the immersion spots through the nano-SILs corresponding to Figs. 2a - 2c, respectively. Upper row: the white spots in each image are the NA0.9 focal spots of the incident light at 642 nm wavelength. Lower row: the scale bars indicate 1 µm.

Figures 3b - 3d show smaller focal spots compared to the non-immersion spot of Fig. 3a. Due to their small size, nano-SILs are robust to experimental errors, such as the small variation of dimensions and shape. Therefore, minor variations of the diameter do not strongly affect their performance, and the three nano-SILs shown in Fig. 2 exhibit approximately the same performance in terms of spot-size reduction and enhancement of the peak intensity. The reference spot in Fig. 3a is the NA0.9 focal spot of the illumination at 642-nm wavelength, whose full-width at half maximum (FWHM) is measured to be approximately 400 nm. The FWHM spot size of the immersion spots is measured to be 300 nm and the peak intensity is 50% higher. We assume that experimental errors, for example the non-ideal shape of the nano-SILs and the resolution of the measurement system, cause the slight discrepancy from the expected value of the spot size reduction.

CONCLUSIONS

We demonstrate that reflow and wetting of non-circular shaped nano-pillars can produce spherical structures, which serve as nano-scale SILs. They show the same performance as nano-SILs fabricated from a cylindrical pattern. The fabricated nano-SILs reduce the spot size by a factor of 1.33 and increase by 50% the measured peak intensity. Investigation of the optimal process parameters, by varying the size of pillars and reflow conditions, is ongoing.

ACKNOWLEDGMENT

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